The worsening impacts of land reclamation assessed with Sentinel-1: The Rize (Turkey) test case

Int J Appl Earth Obs Geoinformation 74 (2019) 57–64

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

The worsening impacts of land reclamation assessed with Sentinel-1: The Rize (Turkey) test case

Esra Erten[a,b,*], Cristian Rossi[c]

[a] Faculty of Science, Technology, Engineering & Mathematics, The Open University, Milton Keynes, United Kingdom
[b] Geomatics Engineering Department, Istanbul Technical University, Istanbul, Turkey
[c] Satellite Applications Catapult, Harwell Campus, United Kingdom

ARTICLE INFO

Keywords:
Sentinel-1
Persistent Scatterer Interferometry
Subsidence
Land reclamation
Seawalls
Landfill
Landslides

ABSTRACT

Massive amounts of land are being reclaimed to build airports, new cities, ports, and highways. Hundreds of kilometers are added each year, as coastlines are extended further out to the sea. In this paper, this urbanization approach is monitored by Persistent Scatterer Interferometry (PSI) technique with Sentinel-1 SAR data. The study aims to explore this technology in order to support local authorities to detect and evaluate subtle terrain displacements. For this purpose, a large 3-years Sentinel-1 stack composed by 92 images acquired between 07/01/2015 to 27/01/2018 is employed and stacking techniques are chosen to assess ground motion. The test site of this study, Rize, Turkey, has been declared at high risk of collapse and radical solutions such as the relocation of the entire city in another area are been taken into consideration. A media fact-checking approach, i.e. evaluating national and international press releases on the test site, is considered for the paper and this work presents many findings in different areas of the city. For instance, alerts are confirmed by inspecting several buildings reported by the press. Critical infrastructures are monitored as well. Portions of the harbor show high displacement rates, up to 1 cm/year, proving reported warnings. Rural villages belonging to the same municipality are also investigated and a mountainous village affected by landslide is considered in the study. Sentinel-1 is demonstrated to be a suitable system to detect and monitor small changes or buildings and infrastructures for these scenarios. These changes may be highly indicative of imminent damage which can lead to the loss of the structural integrity and subsequent failure of the structure in the long-term. In Rize, only a few known motion-critical structures are monitored daily with in-situ technologies. SAR interferometry can assist to save expensive inspection and monitoring services, especially in highly critical cases such as the one studied in this paper.

1. Introduction

The world's largest construction projects, ranging from highways, airports, subways and dams are recently carried out in Turkey (Srivastava and Full, 2016). Although they contribute to the country's economic growth and the demographic transition, the sustainability in cities is facing important challenges due to the lack of land for urban growth. In this context, shorelines are used for residential expansion through land reclamation and they are often exploited for expanding and developing the cities with low cost solutions. Land reclamation is a large business today, and the Ordu-Giresun and Rize-Artvinin airport projects in the Black sea region are conducted by reclamation. The small-town province of Rize, Turkey, has added 350.000 km^2 onto its size over years by reclamation process (Özhaseki, 2018). Rize hosts about a hundred thousand inhabitants and it is located on the Black Sea coast in the north-east of Turkey. This city was reported on February 21, 2018, as: "*Center of Turkey's Black Sea town Rize to be demolished, relocated aimed fears of collapse*" (Özhaseki, 2018). Indeed, the local municipality and the government are planning radical solutions such as the relocation of the entire town center in another place. The collapse risk is due to terrain subsidence. Here, the main subsidence source is the construction of buildings on artificial ground reclaimed to the sea. Since the 60 s, many multi-floors buildings have been erected despite the original planning that was forecasting a maximum of three floors per building. Moreover, new reclamation projects such as the airport construction and the marine urban sprawl zoning plan are encouraged by the authorities. However, it is crucial to monitor reclamation areas to properly plan future construction projects in an efficient way in terms of long term cost and environment.

In this context, structural health measurements can be performed,

* Corresponding author.
E-mail address: eserten@gmail.com (E. Erten).

https://doi.org/10.1016/j.jag.2018.08.007
Received 22 April 2018; Received in revised form 2 August 2018; Accepted 6 August 2018

but they require proper demand from the building owners. In Turkey, city municipalities like Rize provide structural health information but only in response to extreme events such as heavy rainfalls, superloads and evident cracks. These in-situ measurements are very reliable but most of the time it is too late to repair the damage. Therefore, efficient monitoring systems – specifically over reclamation lands – that enable the estimation of structural health are necessary. The availability of geodetic measurements (GPS or leveling) could be very important in this context to perform local scale monitoring. Nevertheless, these standard methods are known to be time consuming, laborious and expensive as they involve intensive field sampling and require the use of special measuring instruments (Halicioglu et al., 2012).

As opposed to these traditional techniques, remote sensing methods using satellite technologies are known to be cost effective and have the advantage of obtaining large-scale information with frequent updates. Synthetic Aperture Radar (SAR) is a mature radar technology and several sensors at different bandwidths are operational and can provide data on a daily base (Moreira et al., 2013). The differential interferometric SAR (dInSAR) technique, which is based on two SAR images, has been intensively used for the monitoring of disasters created by volcanoes (Dirscherl and Rossi, 2018), glaciers (Eriksen et al., 2017; Erten, 2013), landslides (Thomas et al., 2014) and earthquakes (Erten et al., 2010). Thanks to its capability to detect deformations in the order of a fraction of the radar wavelength, dInSAR provides a unique possibility for characterizing deformation over large areas, and is therefore fundamental source of information for damage assessment (Osmanoglu et al., 2016; Aslan et al., 2018; Crosetto et al., 2011; Calo et al., 2015). Nevertheless, dInSAR cannot generally detect movements on the building level and it can be affected by large artefacts due to temporal changes at all levels (e.g. atmosphere, terrain).

Persistent Scatterer Interferometry (PSI) is an interferometric method for deriving two dimensional deformation, i.e. E-W and vertical dimensions when combining ascending and descending geometries, which makes use of the reliability of coherent targets (PSs) in time to tackle dInSAR limitations (Crosetto et al., 2016; Cao et al., 2016; Narayan et al., 2018). The deformation measurement takes place on the PS location. The importance of PSI has been highlighted intensively in city monitoring, which normally includes many coherent scatterers. Among the numerous examples, Cigna et al. (2014) highlights the condition and structural health of the historic centre of Rome, Italy, while Yang et al. (2016), Schunert and Soergel, (2016) show how PSI can be used for monitoring single building deformation. Milillo et al. (2018) shows the tunnel-induced subsidence in London, and Yang et al. (2018); Kim et al., 2005 underline the impacts of reclamation on subsidence in China. All the previous examples have employed high-resolution commercial X-band sensors, namely TerraSAR-X and Cosmo SkyMed, which have been widely used to monitor deformation phenomena induced by human activities in urbanized area (Costantini et al., 2017). A few studies have used coarse-resolution dataset along with PSI processing for city monitoring (Solari et al., 2016). Alternatively, Sentinel-1 C-band data supplies free accessible interferometric dataset with approximately weekly temporal resolution since 2016 in Europe and other selected areas, with huge amount of data available for regular monitoring (Iftikhar et al., 2018; Lasko et al., 2018; Raspini et al., 2018;Iftikhar et al., 2018; Lasko et al., 2018; Raspini et al., 2018 Raspini et al., 2018). On the building level, three measurement scenarios are possible:

1. Multiple measurements on a single building. In this case, the differential settlement can be evaluated and related to critical measures for the building structural health (Nicodemo et al., 2017). Indeed, differential settlement, i.e. variations in the vertical displacement for a structure, is the first cause of building damage and potential collapse (Wroth and Burland, 1974; Boscardin and Cording, 1989). High-resolution sensors can usually provide with many measurements per building, typically at the facade, and can be considered in this case.
2. Single measurement on a building. While a single measure is not sufficient to derive differential settlement, it can still be useful to assess if movements are higher than predictions and provide with indication for further inspections. For instance, the maximum allowable settlement is a well-known problem (Skempton and McDonald, 1956). This number is usually estimated before starting a construction project and strongly depends on the soil type and characteristics and on the building design.
3. No measurement on a building. While this case is clearly not providing any indications, estimates on surrounding buildings can still provide with relevant information on subsidence issues at a larger scale.

A relevant advantage of SAR technology is the provision of all weather data, an important factor for cities in a wet climate. Moreover, the ensured data continuity for the next 25–30 years makes the Sentinel-1 mission an invaluable opportunity for small municipalities and governmental organizations (Plank, 2014). Within this context, the goal of this article is to study Sentinel-1 PS time series across Rize to quantify the subsidence phenomena due to the reclamation and discuss how the Sentinel-1 mission provides an affordable solution for small municipalities to derive useful information. A fact check approach is considered in the study, with several news from the test area taken from local, national and international media.

The paper is organised as follows. Section 2 describes the test site, available SAR data and gives an overview of the PSI processing. Section 3 presents the processing results with four test cases covering different scenarios and Section 4 discusses and summarises the major findings of the study.

2. Description of the test site, available data and processing

The test site, Rize, is located along a bay on the Black Sea in the north-eastern part of Turkey at geographical coordinates (N 41°01′29″ and E 40°31′20″). Its exceptional location between sea and mountains makes Rize a difficult place for industrial development and urban sprawl (see Fig. 1). In this context, being cheap and easy to implement, reclamation process has become an attractive procedure. Indeed, since the 60 s, more than 404,685 m^2 of land (about one-third of Rize's city center) have been reclaimed in Rize by infilling the sea (Özhaseki, 2018).

Rize is nowadays the biggest tea-producing city in Turkey – the fifth biggest tea producer country – with its humid subtropical climate. Beyond the city center, the tea growing lands, which were covered by forests, can be easily seen in Fig. 1. In the last two decades heavy rainfall coupled with deforestation due to agricultural tea land expansion in this mountainous land has causes lots of landslides (Althuwaynee et al., 2018). The Kirechane village, marked in Fig. 1, has been heavily affected by landslides and it is taken as example in the following section.

The Sentinel-1 sensor is regularly acquiring data over Turkey at temporal resolution depending on the area, with minimum orbit repeat cycle of 6 days since 2016. Specifically, all the available data from January 2015 to February 2018 at relative orbit 145 have been considered for this study. A total of 92 acquisitions, taken every 12 days, have been considered. These Single Look Complex (SLC) data, freely available through the Copernicus Open Access Hub (Copernicus, 2018) and acquired in the Interferometric Wide (IW) swath mode, have pixel spacing of about 20m by 5 m (azimuth and range components, respectively). The center scene incidence angle is about 34deg and the acquisitions are taken in ascending geometry.

The data processing needs initial large disk space resources (about 1.5TB). Not all the data is anyhow required (the original swath size is about 250 km). The processing is performed over a selected portion of the data stack centered in Rize, spanning about 30 km along the coast

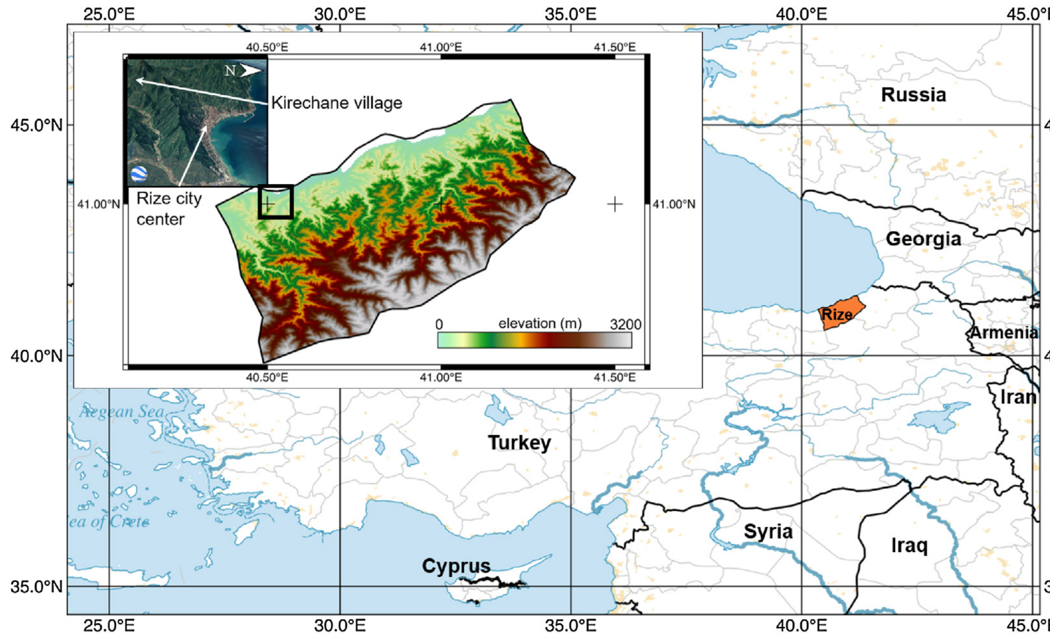

Fig. 1. The location of the study area, Rize, with its topographical character (top-left). The black square over the topographic map delineates the area shown by the Google Earth image, highlighting the urbanization challenges arising from being located between sea and mountains. The background Turkey map shows the location of the province (in orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and 10 km across the mountains. Moreover, only the VV (vertical transmission and reception) polarization is considered for the study.

2.1. PSI processing

Among the various interferometric stacking techniques, PSI has been chosen due to its suitability for urban scenarios (Cigna et al., 2014; Milillo et al., 2018). PSI was invented in the late 90 s and since then it has been widely used to assess surface deformation (Crosetto et al., 2016). The algorithm used for this study (Ferretti et al., 2001; Colesanti et al., 2003) is based on four processing steps: (1) differential interferogram generation; (2) preliminary estimation of displacement velocity and residual heights; (3) final estimation and atmospheric phase removal; (4) results geocoding. A comprhesive description of the processing stages is provided in (Kampes, 2006).

The main parameters are listed in Table 1 and briefly described in the following. First, the differential interferogram generation stage is performed using the Shuttle Radar Topography Mission (SRTM) DEM as input. All the 91 interferograms are considered for the analysis and are referred to the master acquisition, taken on the 10th August, 2016. The interferometric processing is performed with a range multilooking of 3. The preliminary displacement estimation is performed independently on sub-areas of 25 sqkm, for which the reference point is automatically chosen to remove a phase offset from all the interferograms. This estimation is based on candidate scatterers (Permanent Scatterer Candidates, PSC), selected to overcome a specific threshold to ensure small phase dispersion. A threshold of 0.6 for the parameter μ/σ, where μ refers to the temporal mean of the pixel and σ its temporal standard deviation, is chosen and PSCs are targets that exceed this threshold. The subareas are then merged according to a minimum overlap of PSs in their overlap, set to 30%. The atmospheric correction is performed with two filters, specifically a low pass-filter to account for spatial distribution and having a size of 1.2 km, and a hi-pass filter to consider the temporal distribution with a temporal window of 365 days. Finally, a linear displacement model is estimated and points exceeding a coherence value of 0.7 have been chosen for the visualisations in the following subsections.

Table 1
Principal PSI processing parameters.

Parameter	Value
Interferometric range looks	3
Interferometric azimuth looks	1
Parameter estimation sub-area size	25 sqkm
Parameter estimation sub-area PS overlap	30%
PSC μ/σ threshold	0.6
Atmosphere low-pass filter	1.2 km
Atmosphere high-pass filter	1 year
Coherence threshold for visualisation	0.7

The time-baseline plot of the interferometric processing is shown in Fig. 2. The master acquisition is displayed with a yellow dot and the orbital tube reaches maximum perpendicular baseline values of around 140 m (Prats-Iraola et al., 2015). In the following section, the main PSI processing output, i.e. the temporal displacement time series, is analyzed. The displacements are measured in the Line Of Sight (LOS) of the radar sensor, at a right looking direction at 34*dgr*.

3. Results

This section covers the analysis of the dataset presented in the previous section to understand how free-accessible Sentinel-1 data could serve small municipalities to monitor city and could present a vision to facilitate the effectiveness of construction projects. Firstly, we focus on quantifying the terrain subsidence rate of the Rize city centre (Özhaseki, 2018) in Section 3.1. Then, in Section 3.2 several local examples recently reported on media are presented to support the news with quantitative analysis.

3.1. Ground deformation LOS velocity map (2015–2018)

Fig. 3 shows the average LOS velocity map of Rize for the three years considered in the study. As expected, most of the PSs are located in urbanized areas. Here, negative and positive values correspond respectively the movement away from and towards the radar sensor. In the town center, five residential zones of subsidence (specifically the district of Tophane, Pasakuyu, Müftü, Gülbahar, and Engindere) have

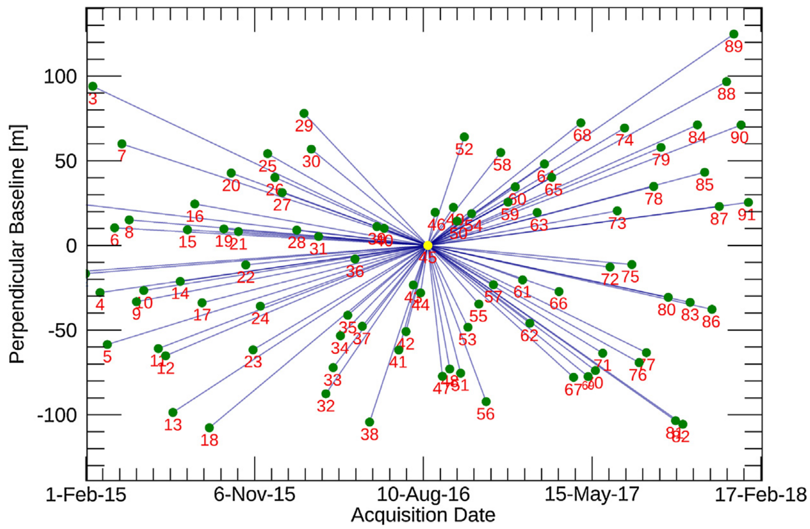

Fig. 2. Temporal (*x*-axis) and perpendicular (*y*-axis) baseline of the Sentinel-1 acquisitions. All interferograms are referred to one master (the yellow dot) image taken on 10 August 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

been identified as all located over the reclamation land. The area without PSs, marked in Fig. 3, is the construction area of a new shopping-mall, and it used to be a stadium. The area close to the construction area of the shopping-mall exhibits the largest range of movement within its district. The cracks in the buildings due to ongoing huge construction project has been recently reported on the local news as well (Rizenin Sesi, 2017). Considering the marked subsidence area, the western side is more stable than the eastern one. In the eastern side, some of the buildings reached approximately −13 mm/yr LOS displacement towards the sensor.

As Fig. 3 highlights, the seawalls and some residential areas exhibit high subsidence rates. It should be noticed that even with its coarser resolution compared to TerraSAR-X and CosmoSky-Med, Sentinel-1 data supplies a remarkable number of PSs for the seawalls. Although the number of PSs over the recreation areas on the shoreline is limited, there are enough samples to see the trend that shows here significant linear patterns of deformation.

3.2. Local test cases

In the following subsections, four different types of subsidence example are chosen to demonstrate how Sentinel-1 can be used for monitoring human and natural induced subsidences. All the cases were reported in national and international media. Section 3.2.1 and Section 3.2.2 analyze the seawalls and the landfill areas, respectively. Section 3.2.3 analyzes the residential area reported at risk of collapse. Finally, Section 3.2.4 moves away from the city center and reports about a village, marked in Fig. 1, belonging to the Rize municipality and affected by landslides. Although not directly related to urban subsidence on reclaimed areas, this example is shown as a complementary demonstration of the capabilities of the system in providing a monitoring solution for subsidence problems in topographically complex areas like the one studied in the paper.

3.2.1. A quantitative analysis to evaluate warning sign along Seawall

One of the first mega construction project in Rize was the harbor expansion through land reclamation. The optical images in Fig. 4 display the construction history of Rize's international port, which started in 1990, was suspended in 2001 due to the economic reasons, resumed in 2013, and was finally completed in 2015. By then, most goods from Rize are exported by ship.

In Fig. 4, the spatial variability of the subsidence over the harbour

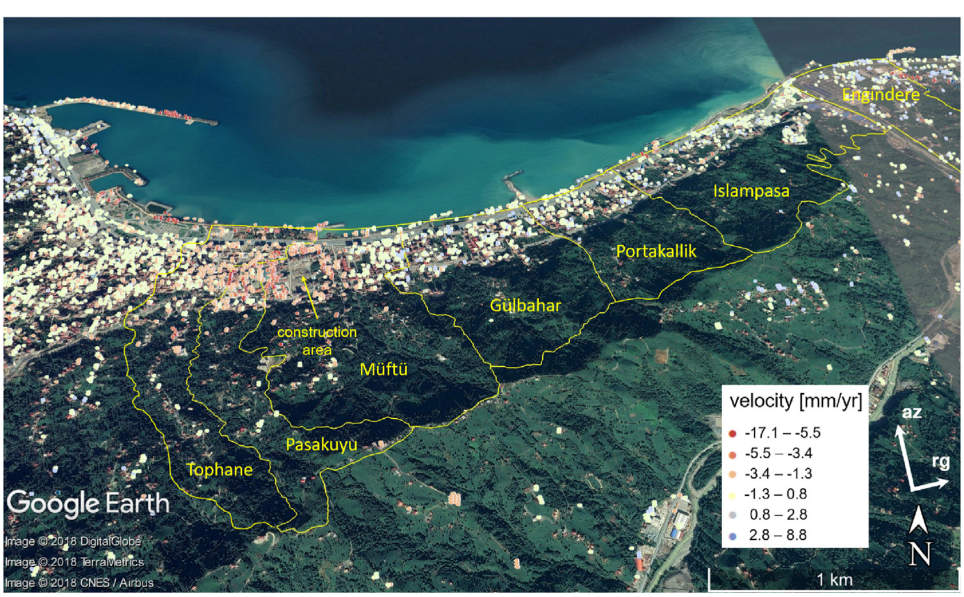

Fig. 3. Average ground deformation map across Rize derived with 92 Sentinel-1 images. Red and blue PSs are corresponding to the velocity away and towards from the Sentinel-1 satellites, respectively. PSs are classified considering the velocity standard deviation. The town districts and the construction area mentioned in the text are marked, and the SAR acquisition geometry (azimuth and range coordinates) is represented at the bottom-right. The optical basemap is extracted from Google Earth.

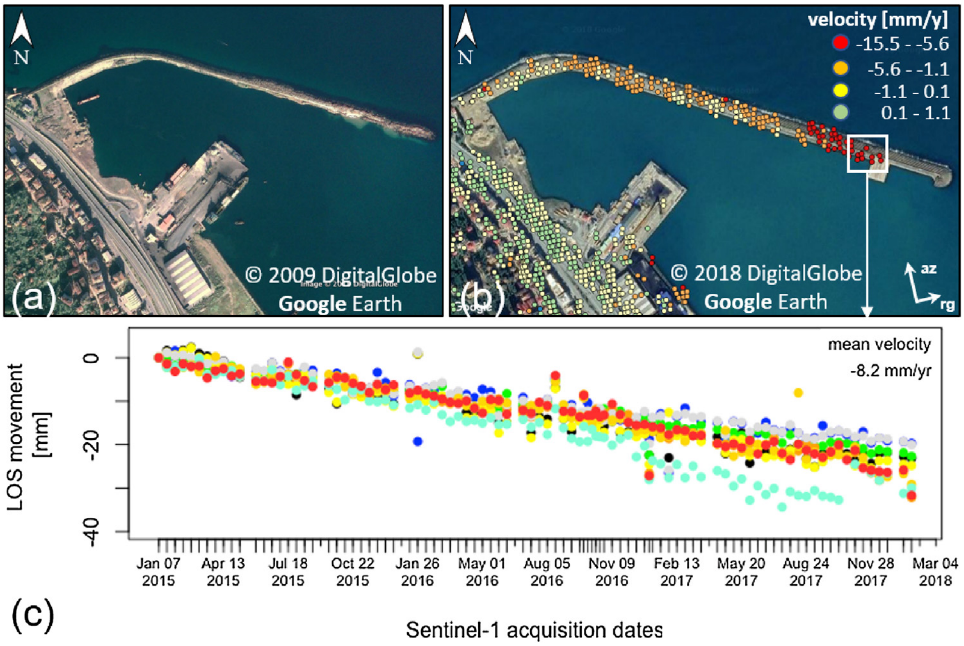

Fig. 4. (a) Optical image of the Rize port in 2009. (b) Same view in 2018, with overlying dots representing the PSs. Highest subsidence is measured at the pier's end. (c) The temporal ground motion plot obtained from the PSs in the white box in (b) shows clear subsiding trends. Different colors represent different scatterers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

can be easily seen, with higher values at its end. The overall harbour (about 2000 m long and 60 m width) presents many measurements. The LOS displacements at selected PSs over the harbour's end, marked in Fig. 4, are also shown. The time series analysis underlines how the newly reclaimed part of the harbour exhibits a moderate subsidence with mean deformation rate of −8.2 mm/yr. The subsidence of Rize's port has been confirmed by the Hürriyet news source, which was published on January 9, 2018: "*The eroding rocks at the harbour are being buried into the sea*" (Kalender, 2018a,b,c). The article discusses whether the type of rock used for the last reclamation guarantees the quality of the fill or not.

3.2.2. Is the reinforcement good enough? The conversion of landfill to build-up area

The second example concerns the construction over previously placed waste. The optical imagery taken in 2009, displayed in Fig. 5, shows an area which was the former landfill site transformed into a natural area. This seaside land was firstly used for recreational purposes including soccer fields, basketball and tennis courts, as well as playgrounds. In late 2012, the recreational facilities were further extended by subsequently adding a swimming pool. Although the construction of the swimming pool was completed in 2013, its opening encountered a series of delays due to the poor construction planning. According to the media records in 2013 (Kacar, 2013), the main reason for this delay lies in the fact that highway-induced vibrations, coupled with soft soil, led cracks in the foundation of the swimming building and hence it was not possible to fill the swimming pools due to the leakage. To tackle this problem, the building's foundation was reinforced and the seawall was extended eastward to provide protection to the building (and its foundation) from the action of waves (see Fig. 5). The swimming pool has been in use since the late 2015s. However, the time series over the swimming pool building given in Fig. 5 warns that in the long term the

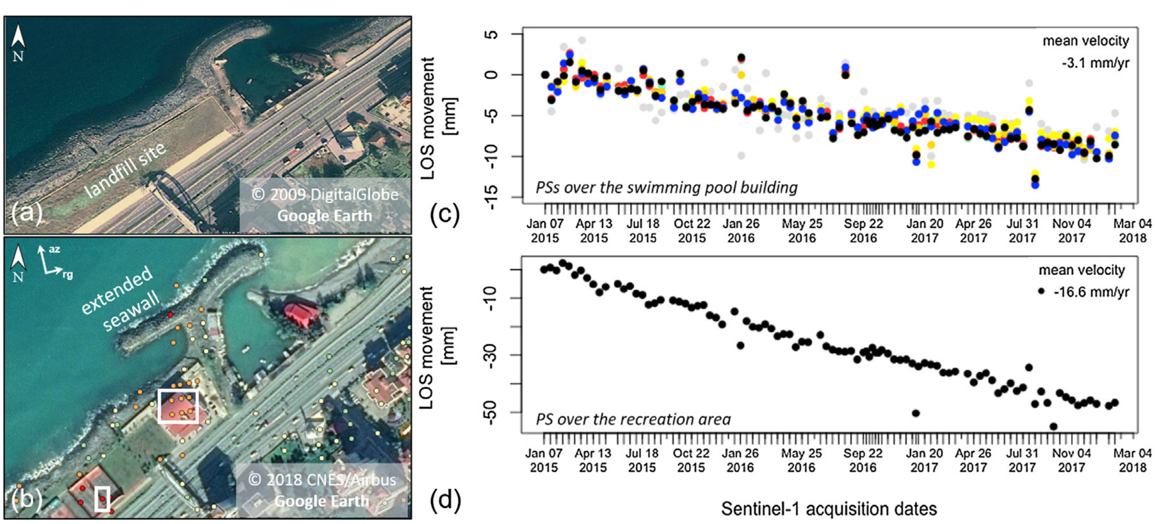

Fig. 5. (a) Optical imagery of the old landfill site in 2009. (b) Same area in 2018, with dots representing the location of PSs. The main changes are the western extension of the seawall and the new constructions in the landfill area. (c) Time series plots over the swimming pool building, marked with the larger white box in (b). The swimming pool building was seen in the national newspapers in 2013, with the headline of "*The indoor swimming pool that do not retain water*" (Kacar, 2013). Different colors correspond to different scatterers. (d) Time serie plot of a PS in the recreation area, marked with the small white box in (b), highlights the subsidence rate of the site.

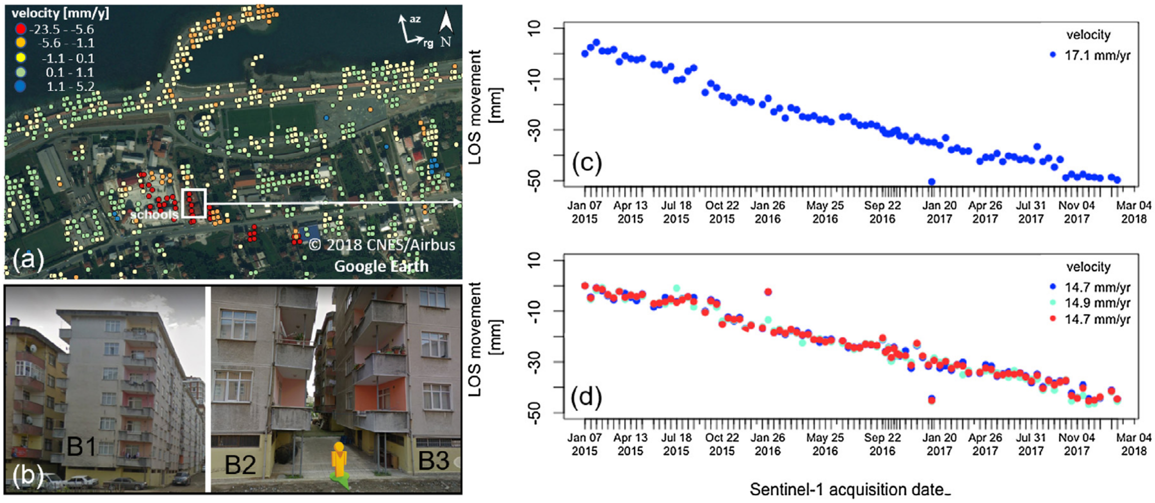

Fig. 6. Sentinel-1 ground motion measurements over the Google Earth image of Engindere district of Rize (a), with Google Maps Street Views (b) acquired in June, 2015, highlighting the subsidence in Deniz housing estate, which is marked with the white box in the first subfigure and its corresponding displacement time series of PSs (c and d). In particular, (c) shows the scatterer associated with block B1 and (d) the the three scatterers associated with blocks B2 and B3.

pool could face with the same problem it had in its planned opening (average rate of 3.1 mm/yr). Additionally, the average LOS velocity of the PS in the recreational area, next to the swimming pool building, reached a rate of 17 mm/yr within the landfill area.

3.2.3. Is really Rize at risk of collapse? Residential areas over reclamation land

The third local deformation analysis focuses on the residential area located on reclamation zone in the district of Engindere. This aspect is of great concern to the municipality since nearly 2700 buildings and 1500 business are in risk of collapse and authorities need detailed information on the structural health of the buildings, as firstly reported on February 21, 2018 by Hürriyet Daily News (Özhaseki, 2018). Fig. 6(a) shows the estimated average LOS velocity over the optical image in the district of Engindere. This map draws the attention to the area indicated in the white square, including building blocks (more than 120 flats) and high-schools, located next to the highlighted buildings on the western side. This residential area has been built in 1988. Here it should be noticed that the road between the schools and blocks was a culvert, one of the lost streams due to heavy urbanization.

The subsidence pattern of PSs over the Deniz housing estate (4 blocks) – marked in the white box – is shown in Fig. 6 with their LOS velocity. All buildings show the same trend with slightly different LOS velocity, 17 mm/yr (Fig. 6(c), building B1), and 14.8 mm/yr (Fig. 6(d), buildings B2-B3). A visual inspection of the street view images in Fig. 6(b) shows how the pending side of the buildings is being strengthened with steel plates between balconies. Recently, concerns have been raised with respect to the structure stability of those buildings: “Scaring precaution: all the buildings in such condition,” Dogan News Agency reported on January 17, 2018 (Kalender, 2018a,b,c). As mentioned in the introduction, differential building settlement is the main trigger to collapse. While here the point density is not sufficient to properly evaluate differential settlement, the measurements can anyhow confirm the subsidence, which can in principle also damage the drainage system and the utilities beneath the building. A particular concern should be raised considering that the subsidence pattern is not uniform in the district but affects the highlighted buildings and the adjacent school complex. Besides the residential area, the seawall in this area exhibits also moderate subsidence trend (~ 5 mm/yr).

This remarkable finding, with other similar examples across Rize, confirms the collapse risk for several buildings.

3.2.4. Are the villages as well at risk? Landslides in susceptible regions

In the processed time series data, the most conspicuous subsidence zone in rural areas lies on the south of Rize, close to the Kirechane village marked in Fig. 1. Like other villages of Rize, the Kirechane village is prone to landslides and mudflows associated with steep slopes, heavy rain and deforestation for agricultural activities. This village has been featured for two days on the news, September 28, 2017 (Kalender, 2017) and March 8, 2018 (Kalender, 2018a,b,c). Kalender (2017) focused on how heavy rain caused flooding on many villages roads and created widespread damage (see the photographs in Fig. 7(a)). Kalender (2018a,b,c) reported the Disaster and Emergency Management Presidency of Turkey (AFAD) statement about the worrying conditions of the structural health of many houses. With the headline, “*A village in Rize is being evacuated due to the fear of landslide*”, the Dogan News Agency mentioned the risk in the village (Kalender, 2018a,b,c). The time series analysis of 12 houses from the same village – given in Fig. 7 (c) – chimed with the news and AFAD report, warning since January 2015 that some houses in the village have been in danger. For this example, unfortunately no street view photograph are available to visually analyze the current situation of the selected houses however there is a high probably that these houses are the ones mentioned on the report by AFAD due to the limited number of buildings in the village. Kalender (2018a,b,c) also stated that the occurrences of heavy rainfall events in 2016 made the soil saturated and more heavy rains are likely to produce more landslide events in the region since then. In Fig. 7(d), the temporal displacement of one PS over a selected building in the village is given with daily precipitation amount. Remarkable LOS movements are estimated in autumn 2016 as a consequence of successive rain events followed by a significant precipitation of about 50 mm in a week. Two main subsidence steps are remarkable in the figure, in October 2015 and November 2016. The correlation with the accumulated monthly precipitation can be evaluated from the figure, where the largest monthly precipitation peak happened in September 2015 and a series of rain events with large rainfall amounts has been measured between June 2016 and September 2016.

This example shows how municipalities can have measures of subsidence peaks in rural residential area to be further inspected. In mixed environments, i.e. urban and rural, an advantage of Sentinel-1 is given by its bandwidth, C-band, which could provide more measurements in vegetated areas compared to X-band systems (TerraSAR-X, Cosmo SkyMed), typically chosen for high-resolution estimates over urban areas. Besides Kirechane village, it has been found that some assets in Kendirli, Pazarköy and Güneysu villages exhibit large subsidences as

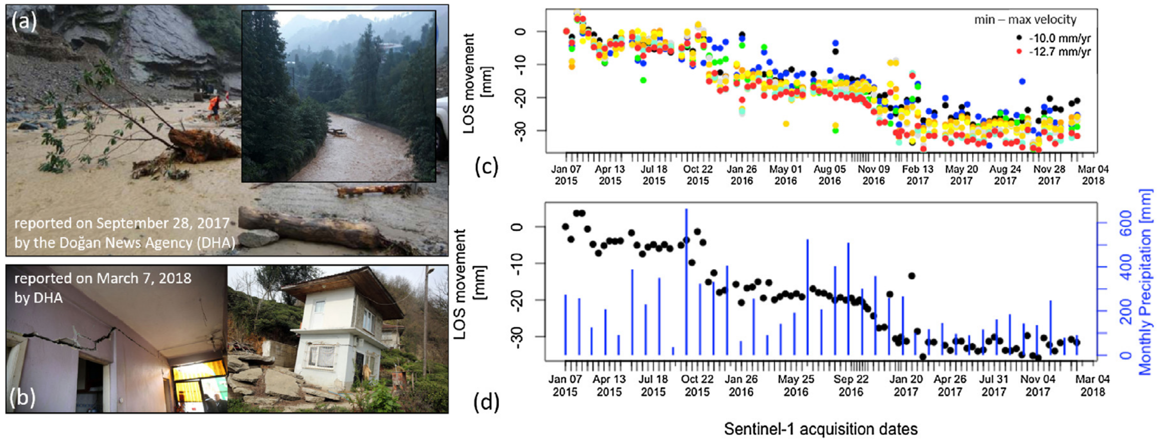

Fig. 7. Photographs taken in Köprülü and Kirechane villages, in mid-October 2017 (Kalender, 2017) (a) and in March 2018 (Kalender, 2018a,b,c) (b). (c) Temporal trends of PSs over the Kirechane village, some of which houses are reported to be evacuated according to the Disaster and Emergency Management Presidency of Turkey, Dogan News Agency reported on March 7, 2018. Different colors represent different scatterers. (d) Temporal trend of a PS over the village with Rize's daily rainfall distribution (https://www.wunderground.com) along with Sentinel-1 acquisitions.

well. Here, Sentinel-1 can be used for landslide monitoring, ideally in conjunction with meteorological, topographic and geological data (Althuwaynee et al., 2018;Bouali et al., 2018). Indeed, the research on assessing landslide impact with PSI is well covered in the literature (Colesanti et al., 2003;Farina et al., 2006;Hilley et al., 2004; Cigna et al., 2013;Tofani et al., 2013).

4. Discussions and conclusions

Interferometric stacking techniques are well known technique for the management of city's infrastructures with high resolution images. In this context, even with its medium resolution, it is shown that Sentinel-1 imagery provides remarkable information for city monitoring. Besides being freely available, the Sentinel-1 temporal resolution is very valuable for monitoring systems, especially in developing countries with low budgets. To show the potential of these data for urban monitoring and to provide quantitative information for subsidence phenomena in Rize, four different types of subsidence occurred in the last three years are reviewed, discussing the assessment of the construction projects in long term. The review has been performed based on public reports and media. Of the four sites, three of them are located in the reclaimed city center and one of them in the rural area. The first example, covering the harbour of Rize, demonstrates the effectiveness of Sentinel-1 at measuring the subsidence/uplift of seawalls, characterized by linear and thin assets. With the large amount of measurements over the seawalls, Sentinel-1 has been shown to be an effective tool for monitoring, predicting and mitigating toe scour at seawalls. The study at the second test site, the landfill area, also suggests that assets over the reclaimed area face with subsidence problems. The rehabilitation process has been substantially performed by the municipality in 2015. However, still exists subsidence in the site, and the movements detected for the only building in the site could indicate a sign of cracking on the foundation, probably going below water level. The third example focusing on residential area intends to aid recognition of the main collapse risk in Rize. To do so, the study focused on one of the areas of maximum detected subsidence. Although local photographs were reflecting the deformation in the district, the PSI analysis allows to reconstruct the deformation pattern in the areas without *in-situ* geodetic measurements. With their changing subsidence rate, this information can be vital for the municipality to predict which areas are at risk of collapse. The last example from the dataset focuses on a village, where roughly 600 people are being evacuated due to the risk of landslide. In this example the village which has been threatened by landslides has been considered. This kind of information is specifically essential for local authorities and for warning local communities about the structural health of their houses. Designing landslide monitoring system is beyond the scope of this paper, but it is clear that Sentinel-1 can provide very important inputs for the management of such a difficult scenario, characterizing by steep mountains and heavy rains.

In addition to these specific examples supported by the national and local newspapers, this work contributes to an understanding of the risks posed by reclamation process in Rize since 1960s. It helps to quantify the subsidence rate in Rize and opens a discussion on how to monitor large-scale construction projects such as Rize-Artvin airport, for which a proper planning of the reclamation process (e.g. the location, the rock type, type of monitoring, etc.) is key to the success of this mega project.

Acknowledgments

This work has been supported by the Scientific Research Projects Coordination of Istanbul Technical University under Project MUA-2017-40799. Authors would like to thank Terri Freemantle, Satellite Applications Catapult, UK, for processing and discussions and 4Maps Information Technologies, Turkey, for providing with *in-situ* information.

References

Althuwaynee, O.F., Asikoglu, O., Eris, E., 2018. Threshold contour production of rainfall intensity that induces landslides in susceptible regions of northern Turkey. Landslides 1–20.
Aslan, G., Cakir, Z., Ergintav, S., Lasserre, C., Renard, F., 2018. Analysis of secular ground motions in Istanbul from a long-term InSAR time-series (1992-2017). Remote Sens. 10 (3), 408. https://doi.org/10.3390/rs10030408.
Boscardin, M.D., Cording, E.J., 1989. Building response to excavation-induced settlement. J. Geotech. Eng. 115 (1), 1–21.
Bouali, E.H., Oommen, T., Escobar-Wolf, R., 2018. Mapping of slow landslides on the Palos Verdes Peninsula using the California landslide inventory and persistent scatterer interferometry. Landslides 15, 439–452.
Calo, F., Abdikan, S., Görüm, T., Pepe, A., Kilic, H., Balik Sanli, F., 2015. The space-borne SBAS-DInSAR technique as a supporting tool for sustainable urban policies: the case of Istanbul Megacity, Turkey. Remote Sens. 7 (12), 519–536.
Cao, N., Lee, H., Jung, H.C., 2016. A phase-decomposition based PS-InSAR processing method. IEEE Trans. Geosci. Remote Sens. 54 (2), 3278–3293.
Cigna, F., Bianchini, S., Casagli, N., 2013. How to assess landslide activity and intensity with persistent scatterer interferometry (PSI): the PSI-based matrix approach. Landslides 10 (3), 267–283.
Cigna, F., Lasaponara, R., Masini, N., Milillo, P., Tapete, D., 2014. Persistent scatterer interferometry processing of COSMO-SkyMed stripmap HIMAGE time series to depict deformation of the historic centre of Rome, Italy. Remote Sens. 6 (12), 12593–12618.
Colesanti, C., Ferretti, A., Prati, C., Rocca, F., 2003. Monitoring landslides and tectonic motions with the permanent scatterers technique. Eng. Geol. 68 (1-2), 3–14.
Copernicus, 2018. Open Access Hub. (Online; accessed 16.04.18). https://scihub.copernicus.eu.

Costantini, M., Malvarosa, F., Minati, F., Trillo, F., Vecchioli, F., 2017. Complementarity of high-resolution COSMO-SkyMed and medium-resolution Sentinel-1 sar interferometry: quantitative analysis of real target displacement and 3d positioning measurement precision, and potential operational scenarios. In: Geoscience and Remote Sensing Symposium (IGARSS), 2017 IEEE International. IEEE. pp. 4602–4605.

Crosetto, M., Monserrat, O., Cuevas, M., Crippa, B., 2011. Spaceborne differential SAR interferometry: data analysis tools for deformation measurement. Remote Sens. 3 (2), 305–318.

Crosetto, M., Monserrat, O., Cuevas-Gonzalez, M., Devanthery, N., Crippa, B., 2016. Persistent scatterer interferometry: a review. ISPRS J. Photogram. Remote Sens. 115, 78–89. https://doi.org/10.1016/j.isprsjprs.2015.10.011.

Dirscherl, M., Rossi, C., 2018. Geomorphometric analysis of the 2014–2015 Barbarbunga volcanic eruption, Iceland. Remote Sens. Environ. 204, 244–259. https://doi.org/10.1016/j.rse.2017.10.027.

Eriksen, H.O., Lauknes, T.R., Larsen, Y., Corner, G.D., Bergh, S.G., Dehls, J., Kierulf, H.P., 2017. Visualizing and interpreting surface displacement patterns on unstable slopes using multi-geometry satellite SAR interferometry (2D InSAR). Remote Sens. Environ. 191, 297–312. https://doi.org/10.1016/j.rse.2016.12.024.

Erten, E., Reigber, A., Hellwich, O., 2010. Generation of three-dimensional deformation maps from InSAR data using spectral diversity techniques. ISPRS J. Photogram. Remote Sens. 65 (4), 388–394. https://doi.org/10.1016/j.isprsjprs.2010.04.005.

Erten, E., 2013. Glacier velocity estimation by means of a polarimetric similarity measure. IEEE Trans. Geosci. Remote Sens. 51 (6), 3319–3327. https://doi.org/10.1109/TGRS.2012.2219873.

Farina, P., Colombo, D., Fumagalli, A., Marks, F., Moretti, S., 2006. Permanent scatterers for landslide investigations: outcomes from the esa-slam project. Eng. Geol. 88 (3–4), 200–217.

Ferretti, A., Prati, C., Rocca, F., 2001. Permanent scatterers in SAR interferometry. IEEE Trans. Geosci. Remote Sens. 39 (1), 8–20.

Halicioglu, K., Deniz, R., Ozener, H., 2012. Digital zenith camera system for astro-geodetic applications in Turkey. J. Geodesy Geoinf. 1 (2), 149–154.

Hilley, G.E., Bürgmann, R., Ferretti, A., Novali, F., Rocca, F., 2004. Dynamics of slow-moving landslides from permanent scatterer analysis. Science 304 (5679), 1952–1955.

Iftikhar, A., Cao, S., Naeimi, V., Paulik, C., Wagner, W., 2018. Methods to remove the border noise from Sentinel-1 synthetic aperture radar data: implications and importance for time-series analysis. IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. 11 (3), 777–786.

Kacar, M., 2013. The Indoor Swimming Pool That Do Not Retain Water. (Dogan News Agency, Online; accessed 16.04.18). http://www.hurriyet.com.tr/gundem/rizede-su-tutmayan-kapali-yuzme-havuzu-25155267.

Kalender, A., 2017. Heavy Rain Causes Flooding Across Rize. (Dogan News Agency, Online; accessed 16.04.18). https://www.dha.com.tr/foto-galeri/rizede-saganak-yagmur-sel-ve-heyelana-neden-oldu/haber-1545866.

Kalender, A., 2018a. Scaring Precaution: All the Buildings in Such Condition. (Dogan News Agency, Online; accessed 16.04.18). http://www.hurriyet.com.tr/ekonomi/buyuk-risk-o-binalara-demir-direkli-onlem-40712585.

Kalender, A., 2018b. A Village in Rize is Being Evacuated Due to the Fear of Landslide. http://www.hurriyet.com.tr/rizede-bir-koy-heyelan-nedeniyle-bosaltiliyor-40763730.

Kalender, A., 2018c. The Eroding Rocks at the Harbour are Being Buried into the Sea. (Dogan News Agency, Online; accessed 16.04.18). http://www.hurriyet.com.tr/rizede-yat-limaninda-eriyen-taslar-suya-gomul-40704140.

Kampes, B.M., 2006. Radar Interferometry: Persistent Scatterer Technique. Springer.

Kim, S.W., Lee, C.W., Song, K.Y., Min, K.D., Won, J.S., 2005. Application of L-band differential SAR interferometry to subsidence rate estimation in reclaimed coastal land. Int. J. Remote Sens. 26 (7), 1363–1381.

Lasko, K., Vadrevu, K.P., Tran, V.T., Justice, C., 2018. Mapping double and single crop paddy rice with Sentinel-1A at varying spatial scales and polarizations in Hanoi, Vietnam. IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. 11 (2), 498–512.

Milillo, P., Giardina, G., DeJong, M.J., Perissin, D., Milillo, G., 2018. Multi-temporal InSAR structural damage assessment: the London crossrail case study. Remote Sens. 10 (2), 287.

Moreira, A., Prats-Iraola, P., Younis, M., Krieger, G., Hajnsek, I., Papathanassiou, K.P., 2013. A tutorial on Synthetic Aperture Radar (SAR). IEEE Geosci. Remote Sens. Mag. 1 (1), 6–43. https://doi.org/10.1109/MGRS.2013.2248301.

Narayan, A.B., Tiwari, A., Dwivedi, R., Dikshit, O., 2018. Persistent scatter identification and look-angle error estimation using similar time-series interferometric pixels. IEEE Trans. Geosci. Remote Sens. 15 (1), 147–150.

Nicodemo, G., Peduto, D., Ferlisi, S., Maccabiani, J., 2017. Investigating building settlements via very high resolution SAR sensors. In: Bakker, J., Frangopol, D.M. (Eds.), Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure. van Breugel, K, pp. 2256–2263.

Özhaseki, M., 2018. Center of Turkey's Black Sea town Rize to be Demolished, Relocated Amid Fears of Collapse. , [Hurriyet Daily News, Online; (accessed 16.04.18). http://www.hurriyetdailynews.com/center-of-turkeys-black-sea-town-rize-to-be-demolished-relocated-amid-fears-of-collapse-127724.

Osmanoglu, B., Sunar, F., Wdowinski, S., Cabral-Cano, E., 2016. Time series analysis of InSAR data: methods and trends. ISPRS J. Photogram. Remote Sens. 115, 90–102.

Plank, S., 2014. Rapid damage assessment by means of multi-temporal SAR – a comprehensive review and outlook to Sentinel-1. Remote Sens. 6 (6), 4870–4906.

Prats-Iraola, P., Rodriguez-Cassola, M., De Zan, F., Scheiber, R., López-Dekker, P., Barat, I., Geudtner, D., 2015. Role of the orbital tube in interferometric spaceborne SAR missions. IEEE Geosci. Remote Sens. Lett. 12 (7), 1486–1490.

Raspini, F., Bianchini, S., Ciampalini, A., Del Soldato, M., Solari, L., Novali, F., Del Conte, S., Rucci, A., Ferretti, A., Casagli, N., 2018. Continuous semi-automatic monitoring of ground deformation using Sentinel-1 satellites. Sci. Rep. 8, 7253.

Rizenin Sesi, 2017. Breaking News in Rize: the Buildings has to be Evacuated! Is the Nearby Construction Reason? , [RizeninSesi Online; accessed 16.04.18). http://www.rizeninsesi.net/2017/06/29/rizede-sok-eden-gelisme-binayi-bosaltin-sebep-o-insaat-mi/.

Schunert, A., Soergel, U., 2016. Assignment of persistent scatters to buildings. IEEE Trans. Geosci. Remote Sens. 54 (6), 3116–3127.

Skempton, A.W., McDonald, D.H., 1956. The allowable settlement of buildings. Proc. Inst. Civil Eng. 5 (6), 727–768.

Solari, L., Ciampalini, A., Raspini, F., Bianchini, S., Moretti, S., 2016. PSInSAR analysis in the Pisa urban area (Italy): a case study of subsidence related to stratigraphical factors and urbanization. Remote Sens. 8 (2).

Srivastava, M., Full, 2016. Speed Ahead for Turkey's “crazy” Construction Plans. [FINANCIAL TIMES, Online; (accessed 16.04.18). https://www.ft.com/content/ab24659c-6f72-11e6-a0c9-1365ce54b926.

Thomas, R., Romero, R., Mulas, J., Marturia, J.J., Mallorqui, J.J., Lopez-Sanchez, J.M., Herrera, G., Gutierrez, F., Gonzalez, P.J., Fernandez, J., Duque, S., 2014. Radar interferometry techniques for the study of ground subsidence phenomena: a review of practical issues through cases in Spain. Environ. Earth Sci. 71, 163–181.

Tofani, V., Raspini, F., Catani, F., Casagli, N., 2013. Persistent scatterer interferometry (psi) technique for landslide characterization and monitoring. Remote Sens. 5 (3), 1045–1065.

Wroth, C.P., Burland, J.B., 1974. Settlement of buildings and associated damage. In: SOA Review, Conf. Settlement of structures. Cambridge. pp. 651–654.

Yang, K., Yan, L., Huang, G., Chen, C., Wu, Z., 2016. Monitoring building deformation with InSAR: experiments and validation. Sensors 16 (12), 2182–2189.

Yang, M., Yang, T., Zhang, L., Lin, J., Qin, X., Liao, M., 2018. Spatio-temporal characterization of a reclamation settlement in the Shanghai coastal area with time series analyses of X-, C-, and L-band SAR datasets. Remote Sens. 10 (2), 329.